Dynamic Characterization of SiC and GaN Devices with BTI Stresses

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Abstract

The use of temperature sensitive electrical parameters for condition monitoring of power devices is widely acknowledged for conventional Si power devices. However, its use for wide bandgap devices is still the subject of research thereby making the electrothermal characterization of these devices a requirement, especially for GaN power devices. This paper investigates and compares the dynamic characteristics of SiC and GaN power devices and how these characteristics are affected by bias temperature instability from gate voltage stress. Results show that turn-ON dI_D/dt increases with temperature in SiC whereas it decreases with temperature in GaN. Turn-OFF dV_{DS}/dt is marginally temperature dependent in both technologies. These electrical parameters can be subject to drift from gate oxide degradation due to charge trapping and threshold voltage drift. Initial V_{GS} stress tests (at the rated voltages) on SiC and GaN devices show no apparent shift in V_{TH}, however more sophisticated test methods using the body diode voltage as an indicator for V_{TH} showed rapid V_{TH} shift and recovery (within a few seconds) in SiC MOSFETs.

1. Introduction

Wide bandgap power devices like silicon carbide (SiC) and gallium nitride (GaN) based FETs are undergoing widespread implementation in industrial applications. There have been significant studies demonstrating improved conduction and switching losses in these WBG devices compared to silicon devices particularly in high frequency applications. Reliability is a major consideration in the industrial implementation of SiC and GaN devices. Condition monitoring using sensors and Temperature Sensitive Electrical Parameters (TSEPs) is increasingly a topic of wide research [1]. TSEPs can be useful for both on-line condition monitoring as well as for reliability characterization, for instance in constant temperature excursion power cycling where TSEPs are needed to control the input power. Various static TSEPs like the ON-state resistance and dynamic TSEPs like current commutation rates have been proposed in literature [1]. However, the use of TSEPs can be affected by the reliability issues of power devices. It is widely known that these WBG devices have gate dielectric characteristics which are different from conventional silicon MOSFETs and IGBTs. In the case of SiC, there is increased interface trap density leading to threshold voltage drift under gate voltage stress [2-4]. This increased interface trap density results from the imperfect oxidation of SiC during device fabrication.

Spontaneous charge polarization and carrier confinement in the 2-DEG formed at the band-offsets between AlGaN and GaN means that GaN HEMTs are typically depletion mode. Enhancement mode GaN requires a p-doped gate layer and, depending on the technology variant, GaN power devices may be voltage driven or current driven (requiring a gate current during the ON-state) [5]. Studies on reliability of GaN power devices are summarized in [6], where threshold voltage V_{TH} shift from gate voltage stress were reported in GaN devices under accelerated stress conditions.

Increased V_{TH} due to BTI can cause higher conduction losses [2] while reduced V_{TH} can cause loss of gate synchronization and potential failure from over-currents in high power applications due to uneven V_{TH} shifts in parallel devices [7] and the susceptibility of parasitic turn-ON can increase due to the reduced V_{TH} [2, 8]. Both compromise the integrity of most TSEPs [9]. In this paper, a comprehensive characterization of the switching transients of SiC and GaN devices is presented as function temperature, of gate resistance and load current. A novel current sensor capable of measuring the temperature dependence of the switching rate in GaN devices is introduced and the impact gate stresses and Bias

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Temperature Instability (BTI) is presented for both SiC and GaN devices.

2. Dynamic Characterization of GaN Devices

The high switching speed of GaN devices demands current sensing with sub-nH parasitic inductance. The Infinity Sensor [10], shown in Fig. 1, provides high bandwidth (225 MHz) current sensing with low insertion impedance (0.2 nH), hence its impact on the switching characteristics of the device is low. The sensor is a planar version of a Rogowski coil, and therefore provides galvanic isolation. Changing currents induce voltages in the two windings shown in Fig. 1. The two windings are connected such that currents under the sensor induce voltages that sum, whereas currents outside of the sensor subtract. Due to the windings being closer together than on a Rogowski coil, a high immunity (around 95% rejection) is achieved [10] to currents outside of the sensing region. The Sensor is placed over current-carrying trace in order to measure the device current, as shown in Fig. 1. The Infinity Sensor used for this study is formed by two symmetrical 1.5 mm × 2 mm coils with a 3 mm gap between them. These dimensions are suited to trace widths of 3-6 mm [10].

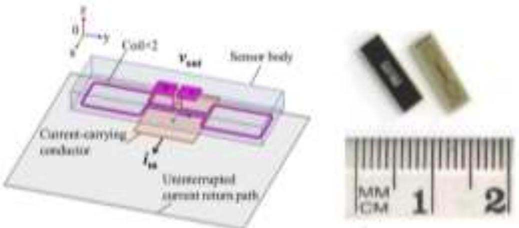
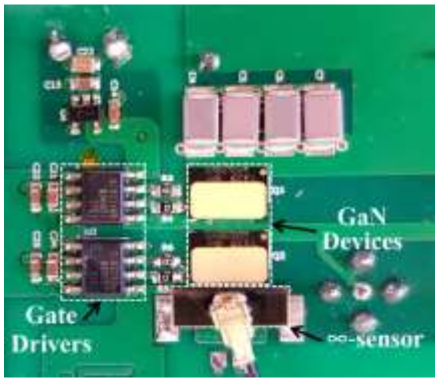
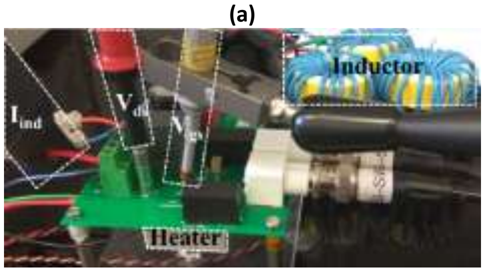


Fig. 1. Infinity Sensor [10]

In this paper, the sensor has been used for characterising the switching transients of the drain current of a GaN device with datasheet reference GS66508 from GaN Systems in a double pulse test setup. Fig. 2(a) shows a picture of the GaN device test set-up together with the gate driver and Infinity Sensor while Fig. 2(b) shows the experimental setup, including the electric heater, load inductor and voltage probes. A voltage probe model PHV 1000-RO from PMK was used for capturing the drain-source voltage transients and a voltage probe model RT-ZP10 from PMK was used for capturing the gate-source voltage transient.



(a)



(b)

Fig. 2(a) GaN HEMT test board (plan view)
(b). GaN HEMT test board with heater and probes

2.1. Turn-ON Characterization:

Fig. 3 shows a simplified circuit diagram of the circuit where the switching tests have been performed. This is a double pulse test circuit, which is widely used for characterization of the switching transients of power devices [11]. The double pulse tests allows to characterize the switching rates of the drain-source voltage, the drain current and the gate voltage characteristics during turn-ON. The switching transients of the low side device are measured as it commutates the inductor load current from/to the high side device, which can be a diode or the body diode of a transistor. V_{DC} is the DC link voltage, C is the DC link capacitance, L is the load inductor, R_G the gate resistance used to drive the device, In this case the bottom side device is turned-ON with a gate voltage V_{GG} while the top side device is used as freewheeling device, holding the gate OFF with a gate voltage V_{GS}=0.

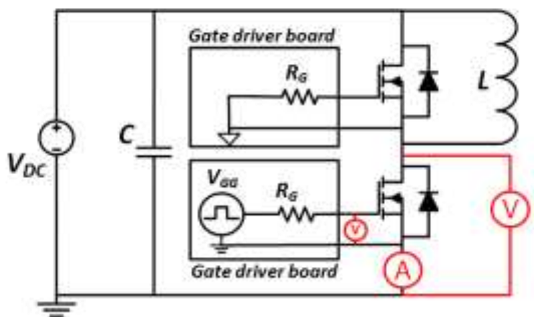


Fig. 3. Double pulse test configuration

The Infinity Sensor is used to measure the currents through the GaN device GS66508. As described in

[10], the output of the Infinity Sensor is a voltage signal proportional to the current switching rate. Fig. 4 shows the measured output of the high-speed current sensor with the GaN device switched with R_G=10 Ω at three different junction temperatures, namely 20, 80 and 150°C. The load current was 20 A, the DC link voltage 400 V and the gate driver voltage was 6 V. The measured output voltage of the sensor can be converted into current and the reduction of the output voltage with temperature indicates a reduction of the turn-ON switching rate.

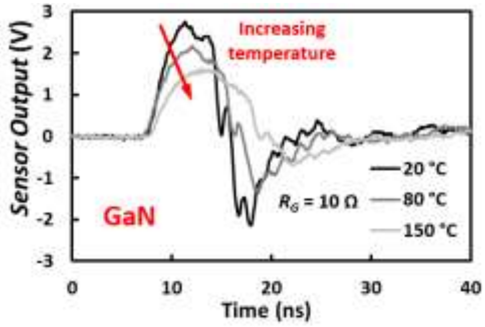


Fig. 4. Output voltage of the Infinity Sensor. Turn-ON transient of a GaN HEMT

The measured turn-ON transients for drain current I_D, drain voltage V_{DS} and gate voltage V_{GS} of the GaN device are shown in Fig. 5. As can be seen from the results, both turn-ON dI_D/dt and dV/dt decrease with increasing temperature. This is due to the negative temperature coefficient of the transconductance g_m in GaN devices. The impact of temperature on the V_{GS} transient is shown in Fig. 5(b), where it is clearly observed how the plateau voltage V_{GP} increases with temperature, as the transconductance g_m reduces.

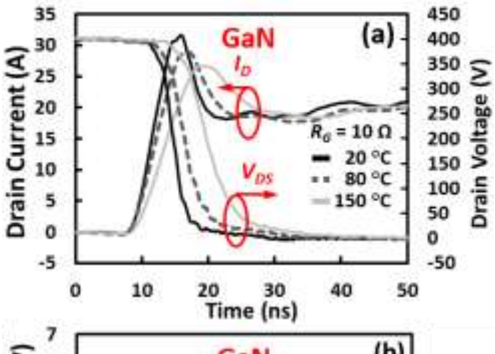


Fig. 5. Turn-ON transients for a GaN HEMT at different temperatures. (a) I_D and V_{DS} (b) V_{GS}

To evaluate the impact of the nominal switching rate on the temperature sensitivity, the GaN HEMT was switched with three different gate resistances (10, 33 and 68 Ω) at three different temperatures (20, 80 and 150°C). Fig. 6 shows the turn-ON current transient for the GaN HEMT switched with 3 different switching rates at 20°C. The measured dI_D/dt for all the switching conditions is shown in Fig. 7, where the results have been normalized against the room temperature switching rate, resulting in a reduction of the switching rate of approximately 40 % for the evaluated gate resistances. If properly calibrated, turn-ON dI_D/dt can be a good TSEP for GaN devices.

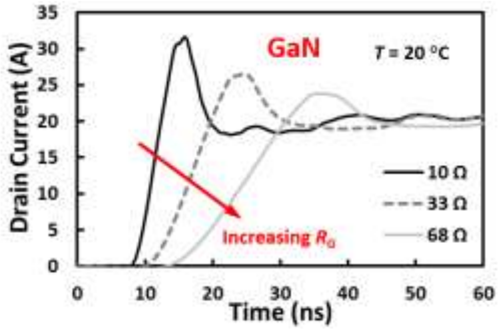


Fig. 6 Turn-ON I_D for different R_G at 20°C

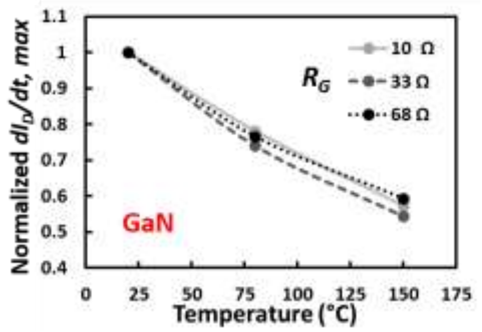


Fig. 7. Normalized maximum dI_D/dt during turn ON for a GaN HEMT vs temperature and R_G

As shown in Fig. 7, using the Infinity Sensor, the peak dI_D/dt can be easily detected. The temperature sensitivity of this TSEP, evaluated using the output of the Infinity Sensor is -8.8 mV/°C for R_G=10 Ω, -4.2 mV/°C for R_G=33 Ω and -1.8 mV/°C for R_G=68 Ω.

It is interesting to compare SiC and GaN, noting that in SiC MOSFETs, the turn-ON dI_D/dt increases with temperature while the gate plateau V_{GP} decreases with temperature [9, 12]. This is shown in Fig. 8 where the turn-ON current transient for a 650 V SiC trench MOSFET at different temperatures can be seen. The positive temperature coefficient of the switching rate is evident. The experimental setup used for the characterization of the SiC MOSFET can be consulted in [12]. It is a more conventional setup where the drain current was measured using a Tektronix current probe model TCP-312.

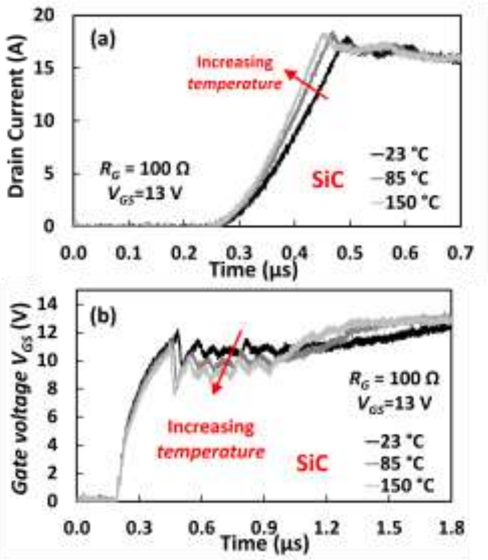


Fig. 8. Turn-ON transients for a SiC MOSFET
(a) Drain current, (b) Gate Voltage

Hence dI_D/dt during turn-ON has a positive temperature coefficient in SiC and a negative temperature coefficient in GaN. This temperature sensitivity can be explained by fundamental device equations. Consider the switching rate at turn-ON is given by Eq. 1, where β is the gain factor, V_{GG} the gate driver voltage and C_{ISS} is the input capacitance of the device.

$$\frac{dI_D}{dt} = \frac{\beta V_{GG}}{R_G C_{ISS}}(V_{GS} - V_{TH})e^{-\frac{t}{R_G C_{ISS}}} \quad (1)$$

The temperature coefficient of the current switching rate at turn-ON is expressed by differentiating Eq. 1 with respect to temperature acknowledging that only β and V_{TH} have temperature dependencies. This is given by Eq. 2.

$$\frac{d^2 I_D}{dtdT} = \frac{V_{GG} e^{-\frac{t}{R_G C_{ISS}}}}{R_G C_{ISS}}\left(\frac{d\beta}{dT}(V_{GS} - V_{TH}) - \beta\frac{dV_{TH}}{dT}\right) \quad (2)$$

Since both β and V_{TH} have negative temperature coefficients, then their derivatives are negative. Hence, Eq. 2 can be written in terms of absolute values as Eq. 3.

$$\frac{d^2 I_D}{dtdT} = \frac{V_{GG} e^{-\frac{t}{R_G C_{ISS}}}}{R_G C_{ISS}}\left(\beta\left|\frac{dV_{TH}}{dT}\right| - \left|\frac{d\beta}{dT}\right|(V_{GS} - V_{TH})\right) \quad (3)$$

Eq. 3 can be written in terms of the transconductance g_m as

$$\frac{d^2 I_D}{dtdT} = \frac{V_{GG} e^{-\frac{t}{R_G C_{ISS}}}}{R_G C_{ISS}}\left(\frac{dg_m}{dT}\right) \quad (4)$$

In power devices, the threshold voltage reduces with temperature due to increased intrinsic carrier concentration from temperature induced bandgap narrowing while the effective mobility reduces with temperature due to increased phonon scattering limiting the carrier relaxation time. This is, though, less apparent in wide bandgap devices.

What Eq. 3 tells us is that the temperature coefficient of the current switching rate at turn ON depends on dV_{TH}/dT and $d\beta/dT$. For SiC, dV_{TH}/dT is greater than $d\beta/dT$, hence, the turn-ON current switching rate increases with temperature since Eq. 4 is positive. Therefore, transconductance increases with temperature in SiC devices. Alternatively, for GaN, V_{TH} is nearly temperature invariant and mobility is more affected by temperature. Therefore, transconductance decreases with temperature in GaN. Hence, in SiC MOSFETs, the negative temperature coefficient of V_{TH} dominates mobility reduction from phonon scattering at higher temperatures. However, in GaN devices, mobility reduction from elevated temperatures dominates V_{TH} reduction from increased intrinsic carrier concentration.

2.2 Turn-OFF Characterization

The turn-OFF transient waveforms for the GaN device switched at three different temperatures with R_G=10 Ω. Fig. 9(a) shows the current and voltage turn-OFF waveforms at different temperatures. Unlike the turn-ON waveforms, the voltage and current commutation rates are temperature independent although the waveforms are time shifted, minimally at 80°C but more apparent at 150°C. An interesting observation is that the gate voltage transient is not temperature sensitive during the turn-OFF transient, as the results in Fig. 9(b) show. Fig. 10 shows the turn-OFF V_{DS} for the GaN device switching 10A, 20A and 30A load currents where it can be seen that the turn-OFF dV_{DS}/dt increases from 37 V/ns to 97 V/ns as the load current is increased from 10A to 30A. This characteristic is lost in circuits where the parasitic inductances limit switching speeds.

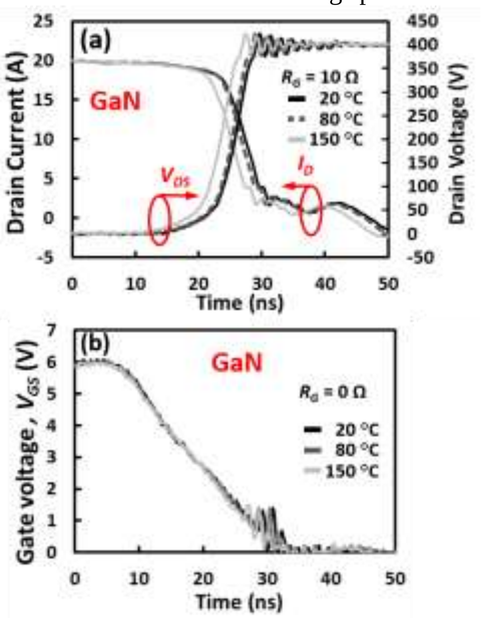


Fig. 9. Turn-OFF transients for a GaN HEMT at different temperatures. (a) I_D and V_{DS} (b) V_{GS}

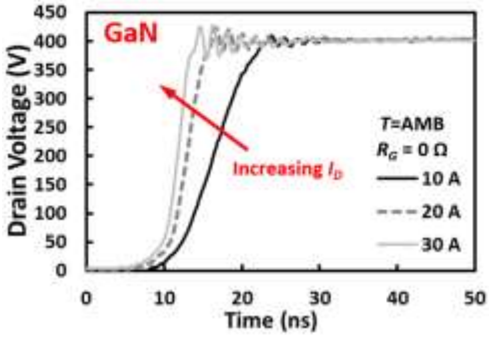


Fig. 10. Turn-OFF V_{DS} transient at different load currents for a GaN HEMT

3. Bias Temperature Instability in WBG devices

Bias Temperature Instability (BTI) refers to the movement of the threshold voltage (V_{TH}) because of V_{GS} stress. This comes from charge trapping and has been reported to be more common in SiC devices than in silicon devices [2]. To date there have been relatively few investigations of BTI in commercial GaN devices compared to the numerous studies on SiC [2-4]. Experiments have been performed on custom made insulated gate GaN MIS-HEMTs [13] and more recently on commercially available GaN devices [14]. In [14] the authors concluded that no observable V_{TH} shift, change in drain leakage current or ON-state resistance was evident after V_{GS} gate stress up to 7 V. However, at about 10 V, the gate current increased significantly and the device failed. In this section the impact of BTI on the switching transients is evaluated for both commercially available SiC MOSFETs and GaN HEMTs.

3.1 BTI and impact on switching transients

Accelerated stress tests are often used to evaluate the reliability performance of power devices under BTI since stress at the rated voltages will require very long times to see V_{TH} shifts. BTI stress can be positive (PBTI) for positive V_{GS} or negative (NBTI) for negative V_{GS}. Fig. 11(a) shows the gate transfer characteristics of a SiC power MOSFET with PBTI and NBTI stresses [9]. In these stresses, V_{GS} was set at 40V for PBTI and -40V for NBTI which is well above the rated gate voltage of the device. The stresses were performed at a junction temperature of 150°C and 16 hours were allowed for V_{TH} recovery to ensure that only permanent drift in V_{TH} was captured. The objective was to perform a highly accelerated stress test to emulate the impact of V_{GS} stress over long durations at the rated voltage. It is clear from the SiC transfer characteristics that there is upwards V_{TH} shift for PBTI and downward V_{TH} shift from NBTI. Similar measurements were performed on silicon IGBTs and are shown in Fig. 11(b) where the gate transfer characteristics are unaffected by BTI stresses.

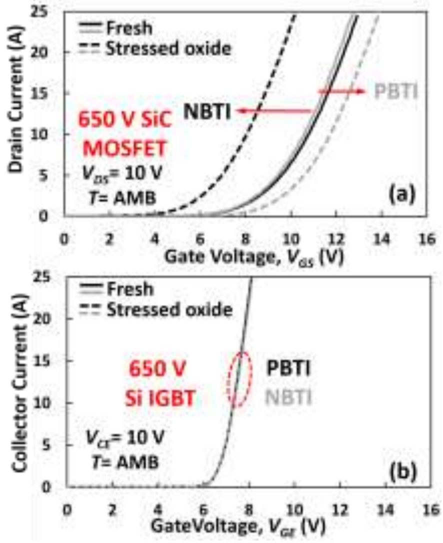


Fig. 11. Gate Transfer characteristics of (a) SiC MOSFET and (b) Si IGBT subjected to PBTI and NBTI stresses [9]

After the application of the stress voltage, the SiC MOSFET was tested in a double pulse test circuit. The impact of PBTI stress on the turn-ON current can be seen in Fig. 12 where there is an 8% reduction of the turn-ON dI_D/dt due to an increase in the V_{TH} from PBTI.

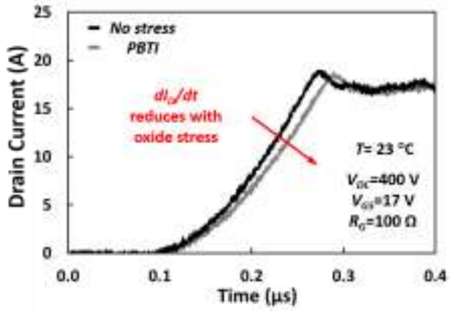


Fig. 12. Impact of PBTI on turn-ON dI_D/dt of a SiC MOSFET

The post-stress measurements performed on the SiC devices indicate permanent V_{TH} drift since sufficient time has been allowed for V_{TH} recovery from charge de-trapping. However, when the rated stress voltage is applied on the SiC device, the V_{TH} shift that results is a temporary shift that corrects itself through trap release after stress removal. It is very important to be able to capture this temporary V_{TH} drift because it can cause reliability problems in the converter. For example, if devices are connected in parallel, uneven V_{TH} shift between devices commutating current from a current source may cause destructive over-currents and electrothermal failure in the device with the lowest V_{TH} during turn-ON. This highlights the importance of capturing the real shift of V_{TH}, its recovery and its implications.

To this end, stress tests are performed using the rated gate voltages and switching transient characterization measurements were subsequently performed to ascertain the impact of the BTI stress on the dynamic characteristics of both GaN and SiC power devices. Commercially available GaN devices are stressed with the rated V_{GS} voltage of 6 V at 150°C for one hour with V_{DS}=0. Both the turn-ON and turn-OFF transients were measured before the stress and after stress removal (in the range of seconds). Fig. 13(a) shows the turn-ON V_{DS} and I_D characteristics pre and post V_{GS} stress while Fig. 13(b) shows the turn-OFF characteristics for the evaluated GaN device.

The measured dynamic characteristics for the GaN device, Fig. 13, were obtained after repetitive switching with the device in electrothermal steady-state. However, transient effects like dynamic ON-state resistance from current collapse and V_{TH} recovery from charge release may have diminished at the time of measurements, hence, when characterising I_D and V_{DS} switching, it is important to account for transient phenomena.

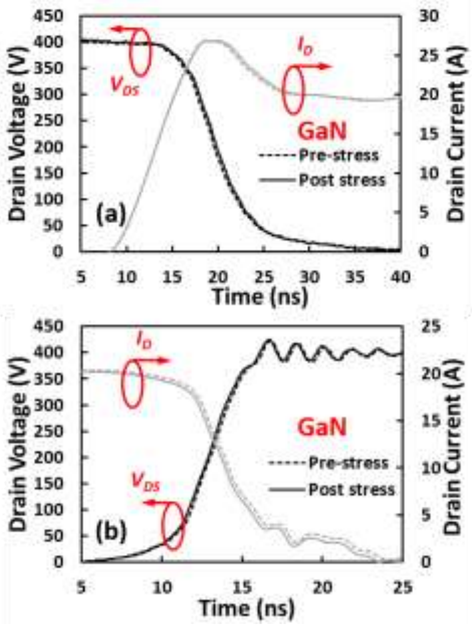


Fig. 13 (a) Pre-stress and post-stress (a) turn-ON and (b) turn-OFF characteristics in GaN device

Similar BTI stress and measurements are performed on SiC power devices to investigate the impact of gate stress on the dynamic characteristics. Commercially available 650 V SiC MOSFETs are stressed with a V_{GS} voltage of 18 V at 150°C for one hour with V_{DS}=0 and the turn-ON and turn-OFF transients are characterized using a double pulse, before and after stress removal (range of seconds). Fig. 14(a) shows the turn-ON V_{DS} and I_D transients before and after gate stress while Fig. 14(b) shows the transients for turn-OFF.

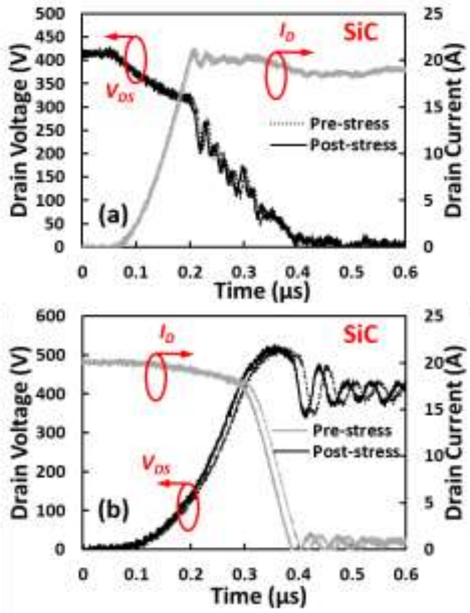


Fig.14. Pre-stress and post-stress (a) turn-ON and (b) turn-OFF characteristics in SiC device

As can be seen from the measurements for both GaN and SiC, there is very little shift in the I_D and V_{DS} transients before and after the stress, with a more apparent shift of the transients during turn-OFF for the SiC MOSFET. However, in the time elapsed between stress removal and device characterization, there is a V_{TH} correction due to charge release which can under-estimate the real shift of V_{TH}. Considering SiC MOSFETs, the peak shift and recovery of V_{TH} due to BTI is a well-known fact [2-3]. It is widely accepted that new characterization techniques are required for BTI measurement in WBG devices since the traditional techniques in silicon do not necessarily capture V_{TH} shift and recovery [2-4]. Novel techniques for BTI characterization, like the use of the 3rd quadrant characteristics presented in [15] can be fundamental for characterization of WBG devices. This technique involves the use of the body diode forward voltage V_{SD} as an indicator of V_{TH} since both parameters are linearly related through the body factor. Hence by passing a small sensing current through the body diode, V_{SD} can be measured during device V_{TH} recovery. Fig. 15 shows how this technique has been applied to a SiC planar MOSFET where the V_{TH} shift and recovery has been characterized using the body diode V_{SD}. Referring to Fig. 15, after a 10 s V_{GS} stress of 17 V, the V_{TH} of the SiC MOSFET increased by 6% and recovered to 2% of its original value after 10 s.

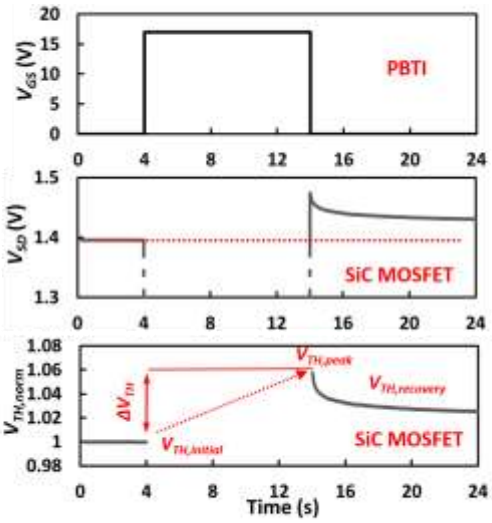


Fig.15 Measured V_{GS}, V_{SD} and $V_{TH,norm}$ waveforms during PBTI stress and recovery in SiC MOSFETs [15]

This recovery after stress removal makes the characterization of BTI-induced V_{TH} shifts challenging. Using high voltage stresses for obtaining a more permanent V_{TH} shift which will allow the evaluation of the impact on the circuit operation may accelerate different degradation mechanisms, whereas if nominal stress values are used the fast recovery of V_{TH} after stress removal may hinder the impact of BTI-induced shifts. This can have implications on qualification of power devices [16].

Conclusions

The switching characteristics and their temperature and BTI dependencies have been compared for both SiC and GaN devices. The temperature coefficient of the switching rate at turn-ON is negative for GaN but positive for SiC. This is because the temperature coefficient of V_{TH} in GaN is lower than SiC and the effective mobility in the 2DEG in GaN is more temperature sensitive than the channel mobility of electrons in SiC. In both technologies, the turn-OFF switching rates are marginally affected by temperature. When subjected to the high temperature gate bias stress at the rated V_{GS} voltage, both technologies show virtually no variation in switching characteristics, however recovery of V_{TH} after stress removal may hinder the true extent of V_{TH} shift, as reported previously. More characterization techniques are needed for V_{TH} shift and recovery quantification in GaN.

Acknowledgements

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